TURBULENT MIXING IN OCEANIC SURFACE AND BENTHIC BOUNDARY LAYERS

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LONG-TERM GOALS

The long-term goal of our research program is to understand, using laboratory experiments, numerical modeling and theoretical analysis, small-scale mixing processes occurring in oceanic surface and benthic boundary layers. The knowledge so gained will be used to develop sound closure parameterizations for oceanic predictive numerical models.

SCIENTIFIC OBJECTIVES

The objectives of the specific effort being reported are to improve the fundamental knowledge of turbulent mixing and diffusion processes occurring in oceanic boundary layers, with special emphases on the surface mixed layer and the wave-current boundary layer in coastal oceans. In the studies of surface mixed layers, the focus is on the penetration of a mixed layer (say, driven by the wind) into a density stratified bottom layer while transporting momentum and mass vertically. Also of interest are the effects of such transports on large-scale circulation patterns and air-sea coupling. Studies on the wave boundary layer are expected to verify the accuracy of currently used bottom boundary layer parameterizations of coastal ocean models.

APPROACH

A major part of the study on the penetration of a surface mixed-layer into an underlying stratified layer was laboratory experimental. The experiments were performed in a recirculating water channel, whereby an upper turbulent layer was driven over a stagnant denser layer to mimic the development of upper-ocean mixed layer. A uniquely designed disk pump was used to drive the flow, and special precautionary measures were used to ensure one-dimensional growth of the mixed layer. Detailed measurements using the laser-Doppler, hot film and particle-image velocimetry techniques as well as flow imaging using the laser-induced fluorescence (LIF) method were used for flow diagnostics. The measurements included the production of turbulent kinetic energy, buoyancy flux, rate of dissipation, internal wave radiation, integral-scales of turbulence and the local Richardson number with a resolution of 2.5 mm (using a specially designed probe). The experiments were conducted by Dr. Eric Strang as a part of his Ph.D. thesis and the P.I., in collaboration with Prof. J.C.R. Hunt of the University of Cambridge, U.K, is carrying a out rapid-distortion-theory based analysis of the problem.

Two approaches are being used to study the physics and transport properties of wave boundary layers. In the first approach, a purely oscillatory turbulent boundary layer, generated by

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an oscillating bottom in a deep fluid layer, is used to mimic the oscillatory flow under waves. This work is performed by Ms. Rajka Krstic as a part of her Ph.D. thesis project. In the second study, carried out by Dr. Heather Earnshaw, an actual wave boundary layer produced by a periodic train of waves traveling on a sloping beach is investigated in a large wave tank of dimensions 104.5 x 3.5 x 6 (ft). In both studies, the parameters of interest are the mean velocity profiles, integral length and velocity scales of turbulence and the upward diffusion of turbulent kinetic energy, momentum and mass. Particle-image, particle-tracking and laser-Doppler velocimetry are used for flow diagnostics.

WORK COMPLETED

The experiments on the deepening of a turbulent mixed layer into a linearly stratified fluid have been completed, and several papers are being prepared to be submitted for publication. The next step would be to extend these studies to encompass non-linear density gradients in the bottom layer.

A part of the work dealing with oscillatory boundary layers has been completed, which includes the evaluation of eddy viscosity as a function of the distance from the bottom and the phase of flow oscillations. Comparisons of oscillatory boundary-layer measurements with other available parameterizations and data were also made. Because of the technical difficulties encountered in using the large wave tank, the work on actual wave boundary layer progressed more slowly than expected. The experimental program is now underway, after overcoming the difficulties.

RESULTS

Dimensional arguments pertinent to the mixed-layer deepening study indicate that the evolution of micro- and macro-scale observables of the flow should be determined by two parameters, namely, the bulk Richardson number $Ri = bD/U^2$ and the frequency ratio $f = ND/U$; here N is the buoyancy frequency, b is the buoyancy jump at the base of the mixed layer and D and U are the depth and velocity of the mixed layer, respectively. The measurement of the mean local gradient Richardson number Ri_g at the mixed-layer base showed that it is related to the bulk Richardson number Ri as $Ri_g = 0.04Ri^2$; see Figure 1. Simultaneous LIF observations of the morphology of the interface showed that the entrainment mechanism, and hence the mixing rate, is closely connected to Ri_g (and hence Ri). It was found that: (i) the interfacial mixing is dominated by Kelvin-Helmholtz (K-H) instabilities when $Ri < 3$ or $Ri_g < 0.4$; (ii) the interfacial wave breaking is dominant when $Ri > 5$ or so ($Ri_g > 1$); (iii) the transition between K-H and interfacial wave-breaking regimes occurs in the range $3 < Ri < 5$; and (iv) the maximum mixing efficiency occurs at $Ri \sim 5$, beyond which there is a rapid fall off of entrainment. These results are generally applicable to the mixed-layer deepening problem, independent of the magnitude of the frequency ratio f or the nature of stratification. For $f = 0$, there is a peak in the entrainment rate at around $Ri \sim 3$, indicating resonant excitation of instabilities at the interface. The mechanism of this resonance was found to be the periodic thickening and thinning of the interface, as a result of local mixing and subsequent removal of mixed fluid by the turbulent eddies. In the regime, $2 < Ri < 5$, a substantial amount of energy available at the interface radiated into the bottom layer via internal waves.

The above results have important implications in the modeling of upper oceanic mixed layers. The results suggest that, contrary to the current mixed-layer modeling practice, there is no need to impose constraints on both Ri_g and Ri, as they are strongly correlated. For example, the prognostic wind-mixed layer model of Price et al. (1986) assumes a cut-off of entrainment above $Ri = 0.6$ or $Ri_g = 0.25$, but the present results show that these two constraints can be combined to form a single cut-off of $Ri_g \sim 1.0$ (or $Ri \sim 5$). Inspection of data taken in strongly stratified oceanic shear-layers, such as equatorial undercurrents (Moum et al. 1992), reveal an interesting phenomenon in that they maintain $Ri_g \sim 1$ or the condition for maximum mixing efficiency of 0.2 - 0.4 (typically, the mixing efficiency is a function of Ri). Whether or not this observation is universally applicable to oceanic stratified shear layers is not known, but this is a phenomenon that should be paid close attention to in future field studies.

Measurements in the oscillatory boundary layer included the velocity profile, thickness of the turbulent boundary layer, turbulent length and velocity scales and the eddy viscosity. The results showed that the eddy viscosity and integral length scales are functions of the distance from the bottom surface and time (i.e. the phase of oscillations). Comparisons of our experimental measurements with the space-dependent eddy viscosity proposed by Grant & Madsen (1979) and the space-time dependent eddy viscosity proposed by Trowbridge & Madsen (1984) revealed a better (qualitative) agreement with the latter, but the experimental eddy coefficients were consistently larger, as is evident from Figure 2. Here, the variation of eddy viscosity with the distance from the bottom can be seen for two different phases of oscillations. Comparisons were made for twelve different phases, and the trends observed were typical of those shown in Figure 2. The results suggest that there is much room for improvement in wave boundary-layer parameterizations.

IMPACT/APPLICATIONS

The results of stratified shear-layer studies are of immense utility in refining existing mixed-layer forecasting models. The oceanic mixed layer is a key entity for a hierarchy of ocean models, ranging from one-dimensional local models to large-scale climate models. In all atmosphere-ocean models, the air-sea coupling is realized through the mixed layer, and hence the accuracy of such models hinges on the mixed-layer parameterizations. Our research shows that certain parameterizations employed in current models can be significantly improved based on insights gained from laboratory and theoretical modeling work. The results of the oscillatory boundary layer studies also show that the existing parameterizations may be inadequate to accurately account for the turbulent transfer of momentum through such boundary layers; this calls for improved parameterizations of eddy-diffusivity coefficients in unsteady turbulent boundary layers such as the wave boundary layer.

TRANSITIONS

With the assistance of Professor James Price of WHOI, we plan to modify the original Price-Weller-Pinkel (PWP) code to incorporate the new findings on the entrainment cut-off. According to Professor Eric D'Asaro (personal communication), the PWP model appears to be sensitive to only one Richardson number constraint, imposed on either Ri and Ri_g, and this observation provides encouragement to proceed with our efforts to adjust the PWP code. The performance of the modified code will be evaluated *vis-a-vis* the available mixed-layer data and against the predictions of the original code. It should be emphasized that the present work not only delineates criteria for the transition between different entrainment regimes, but also elicits the physics associated with such transitions, thus improving the fundamental knowledge base for further refinements to mixed-layer modeling techniques.

Initial results of the oscillatory boundary layer studies indicate that some of the currently employed eddy-diffusivity parameterizations for wave boundary layer models ought to be revisited, but definite conclusions in this regard await the completion of both oscillatory and wave-current boundary layer studies.

RELATED PROJECTS

The P.I. is involved in a National Science Foundation project dealing with environmental turbulent flows. This project investigates general aspects of stratified shear flows and the descent of turbulent blobs of negatively buoyant fluid in such flows (thus mimicking atmospheric microbursts). A project funded by the Army Research Office deals with the evolution of K-H billows in stratified shear flows, with applications to the atmospheric nocturnal boundary layer.

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Figure 1: The relationship between the average local gradient Richardson number and the bulk Richardson number, with the measurements taken within the strongly stratified interfacial zone. Different symbols indicate different experiments.

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Figure 2: A comparison between the eddy viscosity evaluated using the Reynolds stress and mean velocity measurements and that calculated using the model of Trowbridge and Madsen (1984). The results for two phases of the oscillatory cycle (150 deg and 330 deg) are shown. The measurements have been taken above a rough plate oscillating with an amplitude and a period of 10 cm and 5 s, respectively.